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EFFECT OF TEMPERING TEMPERATURE & TIME ON IMPACT PROPERTIES AND MICROSTUCTURE OF SG IRON

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By

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CERTIFICATE

This is to certify that the thesis entitled, "**EFFECT OF TEMPERING TEMPERATURE & TIME ON THE IMPACT PROPERTIES & MICROSTRUCTURE OF SPHEROIDAL GRAPHITE IRON**" submitted by **PABITRA KUMAR MAJHI** and **SANTOSH KUMAR** in partial fulfillment of the requirements for the award of Bachelor of Technology Degree in Metallurgical & Materials Engineering at the National Institute of Technology, Rourkela
(Deemed University) is an authentic work carried out by him under my supervision and guidance.
To the best of my knowledge, the matter enclosed in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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ABSTRACT

Spherodized graphite iron (SG iron)or popularly known as Ductile iron is a special variety of cast iron having carbon content more than 3% and has graphite present in spherical shapes. These compact spheroids helps in maintaining the continuity of the matrix much more than graphite flakes which results in higher strength and toughness with a structure that resembles gray cast iron. Thus it imparts superior mechanical properties which are much higher than other cast irons and which can be comparable to steels. Thus enables SG irons to be used for numerous industrial applications.

Alloying element addition greatly affects the mechanical properties of SG iron with Mn, Cu, Si and Ni being more predominant. While copper helps increasing the hardness causing no embrittlement in the matrix, Ni helps enhancing the ultimate tensile strength without affecting the impact energy values. Therefore addition of Cu and Ni plays key role in determining the end properties of SG iron after heat treatment.

The high ratio of performance to cost which it offers to the designer and end user makes it to be used extensively for industrial uses. However, to enhance the consistency & range of properties of SG iron beyond its properties while in as-cast condition, Heat treatment is a required operation. Tempering & Austempering are two most widely used heat treatment operations in Ductile iron. For example a ferritic iron containing 70-80% ferrite has a yield strength of 350Mpa while a similar material which is given a step quenching treatment shows a yield strength of 550-1250Mpa. Recently developed Austempered Ductile iron (ADI) has good abrasion resistance combined with excellent ductility and toughness.

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CHAPTER 1: INTRODUCTION

Spheroidal graphite iron was discovered in the year 1948. However, «lf coke (which is high in sulfur) had not been used for melting iron & if high purity ores had been used, then ductile iron would have been accepted as the normal form of iron, with flake graphite iron only being discovered much later as an accident of adding S and O. This seems to have been close to the situation in China where spheroidal graphite irons were produced over 2000 years ago [Han91].
» in [Har97].

The term Cast iron refers to an alloy of iron having more than 2% of carbon. The brittle behavior associated with the cast iron is an outdated and widely spread misconception which implies all cast irons are brittle & none of them are ductile in nature. Ductile iron is one form of cast iron which is ductile and it offers the designer a unique combination of high strength, fatigue resistance, wear resistance, toughness and ductility in addition to good castability, machinability and damping properties. Unfortunately these properties of SG iron are not widely
Well known because of the misconception about its brittle behavior.

Ductile iron or SG iron was discovered in 1948 at the American Foundry men Society Annual Conference. It was seen that by adding magnesium before pouring caused the graphite to form nodules instead of flakes. This results in a new material, with excellent tensile strength & ductility. Summing up these mechanical properties of SG Iron to the advantages already offered by cast iron soon led to it finding its way into virtually every mainstream area of engineering, in many ways replacing existing steel castings or forgings due to achievable cost savings. It is shown that, recent process and developments open new avenues to this family of materials.

SG iron is an alloy of iron and carbon having nodules or spheroids of graphite embedded in a ferrite-pearlitic matrix. The nodules are compact spheres and are sharp and regular. The graphite occupies about 10-15% of the total material volume and because graphite has negligible tensile strength, the main advantage of its presence is to decrease the effective cross-sectional area, which means that ductile iron has impact strength, modulus of elasticity and tensile strength proportionally lower than that of a carbon steel of otherwise similar matrix structure.
The matrix may vary from a soft ductile ferritic structure through a hard and higher strength pearlitic structure to a hard higher and comparatively tough martensitic structure. General engineering grades of ductile iron commonly have the structures which are ferritic, ferritic/pearlitic or pearlitic. Controlled processing of the molten

iron precipitates graphite as spheroids instead of flakes. The spherical shape of the graphite eliminates the material's tendency to crack and helps prevent cracks from spreading. The properties of SG iron are affected by elements like Si, Mn, Cu, Ni etc. Except carbon almost all the elements increase hardness and tensile strength.

While except Si, all other elements promotes pearlite, except Si, Cu, Ni all other elements promote carbide formation.
Experiments have shown that heat treatment operations can improve the properties of SG iron to such an extent that it may overcome the properties shown by steels. Today austempered ductile iron is considered a bright prospect having a good combination of properties. Combining the tensile strength, ductility, fracture toughness and wear resistance of steel with production of economics of a conventional ductile iron, ADI offers the designer a great opportunity to create superior components at reduced cost.

CHAPTER 2: S.G. CAST IRON

2.1 TYPES OF CAST IRONS

Cast iron generally contains more than 2% C and a variety of alloying elements. These are generally classified by a rather simple and archaic system. Classification is done on the basis of the appearance of their microstructure, their fracture surface & properties. There has been two class of cast irons historically, one having a white fracture appearance and other having a gray fracture appearance, named as *white cast iron* and *gray cast iron* respectively. Those irons having both white and gray appearance are called *mottled iron*. It is interesting to note that these names are still applicable today. Subsequently, other cast irons have evolved which have their name derived from their mechanical property, such as *ductile iron & malleable iron*. More recently *austempered ductile iron* and *compacted graphite iron* have been introduced. There are four factors which lead to the different types of cast irons namely, the carbon content, the alloy, the impurity content, the cooling rate and the heat treatment after casting. These parameters control the composition as well as the form of parent matrix phase present.

Cast irons can be broadly classified into these 5 categories.

1. Gray cast irons:

This is the most common type of cast iron found. It has a gray fracture surface due to the presence of high volume of graphite *flakes*. Carbon present in graphite form is more stable than that of carbide form. While cooling, if it is subjected to a controlled cooling rate & adequate alloying addition then carbon gets precipitate out as graphite flakes. It contains high amount of Si because it promotes the formation of graphite during solidification. Gray cast irons have very low ductility but are useful as they can easily be casted to complex shapes and are inexpensive. They also have very low impact resistance.

2. White cast iron:

White cast iron can be obtained by rapid solidification of gray iron. Its fracture surface is white in color. Graphite flakes are not present in this type of cast irons rather; an iron carbide network is present that gives a white fracture surface. The Si content is less to minimize the graphitizing effect. They possess high hardness and excellent abrasion resistance. But they also possess excessive brittleness and poor machinability. To enhance wear resistance generally Cr, Ni& Mo are added to it.

4. Malleable cast iron:

It is produced by heat treatment of white cast iron in which the iron carbide network decomposes into *temper carbon*. This process is known as malleabilization that includes two stages of annealing. Due to the absence of hard and brittle carbide phase, iron becomes malleable. Disadvantage of this cast iron is its limited section thickness & prolonged annealing cycles.

3. Mottled iron:

This type of cast iron is not produced intentionally & results from a transition between gray & white cast irons. It is not necessarily a desirable material.

5. Spheroidal graphite cast iron or ductile iron:
This is produced by adopting special alloy addition & proper rate of cooling so that, carbon can be converted into spherical forms which can be used in those fields where carbon in temper form or flake form cannot be used. The nodules are formed while solidification & not during heat treatment. SG Iron can be of three different types namely, ferritic, pearlitic/ferritic, and martensitic. It possesses excellent mechanical properties which is comparable to that of steels.

There is a subclass of SG iron namely **Austempered ductile iron**. It also has the same spherical graphite as in ductile iron but the matrix is a combination of bainite & stabilized austenite. Austempering is necessary to get this type of cast iron. Here graphite is present in compact form & shape of the graphite is controlled by minor alloying addition. ADIs have excellent mechanical properties such as high tensile strength, ductility & wear resistance.

TYPES OF SG IRON

Depending upon the matrix phases, SG iron can be classified into four groups.

1. Ferritic
2. Pearlitic
3. Martensitic
4. Austenitic

SG irons are generally ferritic type. But low yield strength and high ductility makes it difficult to be used in certain applications. Thus if some carbon is left intentionally in cementite form, property gets enhanced. Such type of SG iron is referred as pearlitic SG iron. If the rate of cooling is very high then the matrix will get converted into martensite. Due to its ductile nature it has limited applications. Thus the matrix may vary from a soft ductile ferritic structure through a hard and higher strength pearlitic structure to an austenitic structure.

2.2 AVERAGE COMPOSITION OF SG IRON

ELEMENTS	CONTENT (Wt.%)
Carbon	3.0-4.0
Silicon	1.8-2.8
Manganese	0.1-1.0
Phosphorus	0.01-1.0
Sulphur	0.01-0.03

Table 2.2: Average composition of SG iron

2.3 PRODUCTION OF SG IRON

1. Desulphurization:
Sulphur helps in the growth of graphite flakes. Thus while producing SG iron the raw materials should have low sulphur content (<0.1%). Sulphur should be removed during melting or by addition of a desulphurising agent like calcium carbide or soda ash.

2. Nodulising:
Magnesium is added to the bath to tie up sulphur and oxygen and radically change the graphite growth morphology. Magnesium reacts with oxygen to form highly stable MgO which floats on the surface &can be skimmed off easily. Oxygen content thus reduces from typical levels of 90-135ppm to about 15-35ppm. Magnesium also reacts with sulphur to produce less stable MgS. Due to low solubility of magnesium in the metal and because of its volatile nature; reaction can become reversible if losses are not taken care of. Si is added for additional deoxidation. Group 1A, 2A, 3B elements can also be added for tying up sulphur and oxygen. Cerium forms highly stable oxides with S and O and is less volatile than Mg. Addition of Mg is done when the melt is at 1500^0C but Mg vaporizes at 1100^0C. Magnesium being lighter floats on the bath and being reactive burn off at the surface. Hence it is generally added as Ni-Si-Mg, Ni-Mg alloy or as Magnesium coke to reduce the violence of the chemical reaction and to have saving in Mg. Thus magnesium addition plays an important role in the manufacture of SG iron.
After nodulation, inoculants like magnesium have its spherodising effect on the graphite structure such that graphite nodules can be formed.

3. Inoculation:
The inoculation of cast iron involves the addition of small amounts of a material (inoculants) to the molten metal either just before or while pouring. Inoculation enhances the number of points available for the precipitation and subsequent growth of graphite. This effect many times referred as increasing the degree of nucleation of the iron. It can be seen that high levels promote graphite structure whilst low levels can result in the formation of either mottled structure or white irons. The need for a high level of nucleation increases as cooling rate increases, i.e. section size decreases. In addition to its effect on graphite morphology, magnesium is a powerful carbide promoter and as a result, comparable to gray irons, there is a greater tendency for ductile irons to solidify with white or mottled structure. The primary purpose of inoculating ductile irons is to suppress formation of chill and mottle.
In addition, inoculation is important in maintaining good nodule shape and high nodule numbers. Graphite is not effective Inoculants for ductile irons and all effective inoculants are based on silicon.

The most widely used is foundry grade ferrosilicon, containing about 75% of silicon. This alloy must contain small amounts of aluminum and calcium, in order to be fully effective; the amounts required are about 1.5-2.05 aluminum and about 0.3-1.0%. The inoculating effect produced initially increases as the amount of inoculants is increased, but the effect soon begins to level off. A situation is reached where the extra inoculating benefit obtained is too small to justify for the increased addition. Usually, suppliers recommend smaller additions of the proprietary inoculants to achieve the same degree of nucleation. This partly compensates for their increased cost and has the advantage of decreasing the amount of silicon added.

4. Solidification of SG iron:

Solidification of SG iron is always associated with proper under cooling. Graphite nuclei grow slowly & then are surrounded by austenite. This combination of austenite & graphite corresponds to the eutectic point at eutectic temperature. Austenite, that gets supersaturated with carbon cools and a new equilibrium is established at the graphite/austenite interface. The excess of carbon diffuses towards the graphite nodule where it precipitates out.

CHAPTER 3: PROPERTIES & APPLICATION OF SG IRON

3.1 PROPERTIES OF SG IRON

We take into account the mechanical properties, physical properties and service properties while we consider any material to be used for industrial applications. While mechanical properties takes into account tensile strength, hardness, elongation, proof stress, elastic modulus, impact and fatigue strength, physical properties include damping capacity, conductivity and machinability. The material to be used should be able to survive under the service conditions which can be determined by its wear resistance, heat resistance and corrosion resistance.[5]

Properties:

Tensile strength: Ductile iron has higher tensile strength generally ranging from 414Mpa for ferritic grades to 1380Mpa for martensitic or austempered ductile iron grades.
Yield strength: It is the stress at which the materials begin to have plastic deformation. For ductile irons generally 0.2% offset yield strength is calculated. Yield strength of ductile iron ranges from 275Mpa for ferritic grades to 620Mpa for martensitic grades.

Ductility: Ductile irons have considerable ductility. Elongation can sometimes as high as 25% which is applicable for lower grades only. Austempered ductile irons have the best combination of strength and ductility.

Modulus of elasticity: Ductile irons show a proportional stress-strain limit which looks similar to that of steels but is hampered by plastic deformation. The modulus of elasticity of ductile varies from 162-170Gpa.
Easy to cast: High fluidity enables it to be easily casted.
Excellent corrosion resistance: Ductile irons have very good corrosion resistance property.
Machinability: Has a very good machinability due the graphite which is available in free form. Thus chip formation is easier.

Cost per unit strength: It is lower than most of the materials. Thus has wide range of applications for which it can be used.

3.2 EFFECT OF ALLOYING ELEMENTS ON PROPERTIES OF SG IRON

1) **Silicon:** As the Si in the ductile iron matrix provides the ferritic matrix with the pearlitic structure. Silicon enhances the performance of ductile iron at elevated temperature by stabilizing the ferritic matrix and forming the silicon reach surface layer, which restricts oxidation.
The potentially questionable influences of enhancing silicon content are:

i). Reduced impact test energy.
ii). Increased impact transition temperature.
iii). Decreased thermal conductivity.

Si is used to promote ferrite and to strengthen ferrite. So Si is generally held below 2.2% while producing the ferritic grades and between 2.5% and 2.8% while producing pearlitic grades

2) **Manganese:** As it is a mild pearlite promoter, with some necessary properties like proof stress and hardness to a small extent. As Mn retards the onset of the eutectoid transformation, reduces the rate of diffusion of Carbon in ferrite and stabilize cementite (Fe_3C).But the problem here is the embrittlement caused due to this, therefore the limiting range is between 0.3-1.0.

3) C**opper:** It is a strong pearlite promoter. It enhances the proof stress with the tensile strength & hardness with no embrittlement in matrix. Therefore in the pearlitic grade of the SG iron the copper is kept between 0.4- 0.8% and is a contaminant in the ferritic grade.

4) **Nickel:** As it helps in increasing the U.T.S without affecting the impact values. So it can be in the range of 0.5-2.0. It strengthens ferrite, but has much less effect than Silicon in reducing ductility. But there is the danger of embrittlement with the large additions; in excess of 2%. Due to the high cost it is generally present as traces in the matrix.

5) **Molybdenum:** It is a mild pearlite promoter. It Forms intercellular carbides especially in heavy sections. Increases proof stress and hardness. There is danger of embrittlement, giving low tensile strength and ductility. It also improves elevated temperature properties.

6) **Chromium:** As it prevents the corrosion by forming the layer of chromium oxide on the surface and stops the further exposition of the surface to the atmosphere. But as it is strong carbide former therefore not required in carbide free structure.

7) S**ulphur and Phosphorus:** As ‘P’ is kept intentionally very low, as it is not required because it causes cold shortness and so the property of ductile iron will get deteriorated. But the addition of Sulphur is done for better machinability, but it is kept around 0.009 and maximum 0.015%.As the larger additions of Sulphur may cause the hot (red) shortness.

3.3 APPLICATION OF SG IRON

Much of the annual production of ductile iron is in the form of SG iron pipe, used for water & sewer lines. SG iron pipe is stronger & easier to tap, requires minimum support & provides greater flow area compared to pipe made from other materials. In difficult terrain it can be better fitted than, concrete ,PVC, polyethylene, or steel pipe.

Ductile iron is specifically useful in many automotive components, where strength needs more than that of aluminum but do not necessarily require that of steel. Some other industrial utilities include off-highway diesel trucks, agricultural tractors, class 8 trucks, and oil well pumps. [2]

Since ductile irons have properties similar to steels their application has been extended to

- *Thrust bearing.*
- *Hydraulic clutch in diesel engine for heavy vehicle.*
- *Check beam for lifting track.*
- *Four throw crankshaft.*
- *Fully machined piston used in large marine diesel engine.*
- *Bevel wheel.*
- *Fittings overhead the electric transmission lines.*
- *Caskets in Nuclear Industry*
- *Tractor life arm.*
- *Frame for high speed diesel engine.*
- *Mine cage guide brackets.*
- *Gear wheel & pinion blanks & brake drum.*
- *Machines worm steel.*
- *Flywheel.*

CHAPTER 4: HEAT TREATMENTS

To fully utilize the range of properties beyond the limits of those produced in as-cast condition; Heat treatment is a very valuable tool. The heat Treatments can be carried out on Spheroidal Graphite Iron to achieve the following properties:

1. Increased toughness and ductility,
2. Increased strength and wear resistance,
3. Increased corrosion resistance,
4. Stabilized microstructure, to minimize growth,
5. Equalized properties in castings with widely varying section sizes,
6. Improved consistency of properties,
7. Improved machinability, and
8. Relieved internal stresses.

The following heat treatments were employed for our study:

1. Austenitising
2. Tempering

4.1 Austenitising

This is a heat treatment process in which the ferrous alloy is held above the upper critical temperature for a sufficiently long time to ensure that the matrix has fully transformed to austenite. Austenitising is done prior to any heat treatment process to produce a uniform matrix.

4.2 Tempering

It is the heat treatment process in which the quench-hardened or normalized ferrous alloy is reheated to a temperature below the transformation temperature and cooling is done at any desired rate. Tempering is done to relieve thermal residual stresses and for improving ductility and toughness. The enhancement in ductility by tempering leads to depreciation in the hardness and strength.

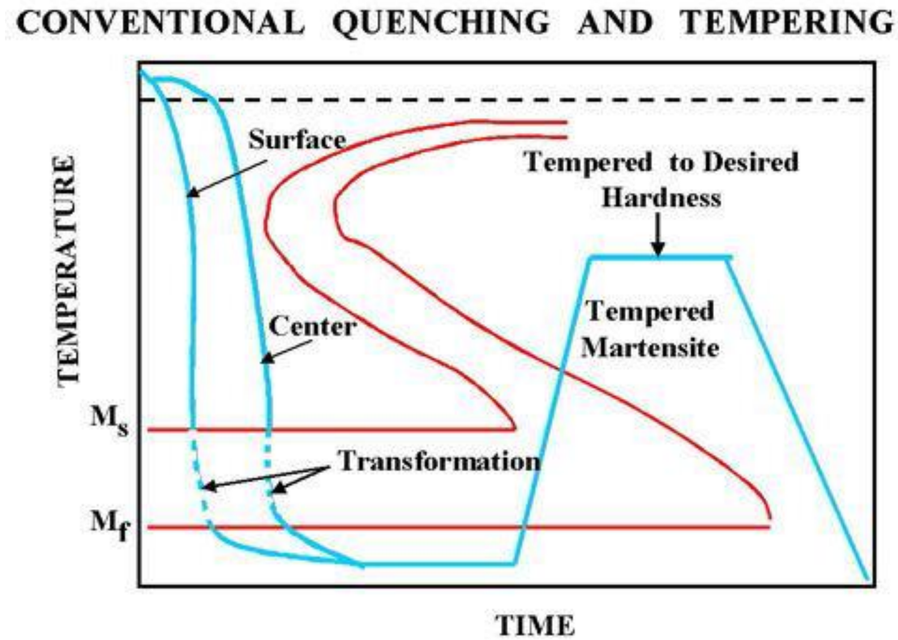


Figure 4.2: Conventional Quench & Tempering Process

Tempering results in:

1. Reduced brittleness.
2. Reduced Hardness and Strength.
3. Enhanced ductility and Toughness.

CHAPTER 5: EXPERIMENTAL PROCEDURE

The various steps that were carried out are:

1. Specimen Preparation,
2. Heat Treatments,
3. Polishing,
4. Microstructural study.
5. Mechanical Property Study.

5.1 Specimen Preparation

The specimen in as-cast condition had the following composition:

ELEMENT	CONTENT (Wt. %)
Carbon	3.52
Silicon	2.04
Manganese	0.17
Phosphorus	0.022
Sulphur	0.009
Chromium	0.02
Nickel	0.11
Molybdenum	0.001
Copper	0.02
Magnesium	0.042
Cerium	0.007
Iron	Rest

Table 5.1: Specific composition of SG Iron

Six pieces of Impact specimen were cut into specific size according to ASTM standards.

5.2 Heat Treatments:

The various heat-treatments employed for our study were:

1. Austenitising
2. Quenching
3. Tempering

AUSTENISING:
The specimens of each type were heated to austenitize at 850 ^{0}C for 1 hour inside the furnace one after another.

QUENCHING:
Both the austenized samples of each type were quenched in an oil bath maintained at room temperature.

TEMPERING:
These specimens were now put inside the furnace maintained at 200^{0}c and 400^{0}c Separately and then were taken out of the furnace one by one for air cooling after duration of 1hr, 1.5hr & 2 hours.

5.3 Polishing & Etching:

Firstly all the specimens are polished using belt grinder. Then the specimens were polished using different grades of emery paper in a sequential order i.e. starting from 1/0, 2/0, 3/0 to 4/0 emery papers. Then cloth polishing is done using paste of alumina powder& water. Further it is taken for diamond polishing and then it is taken for etching. The etchant used is Nital (2% HNO_3 - Ethanol) which attacks the grain boundary & helps in distinguishing different grains. Then specimens are taken for microstructural study.

5.4 Microstructural Study:

Herein the specimens are kept under an optical microscope & the magnification is adjusted at 100 X. Thus footages are taken at different places which helped in distinguishing the phase present, percentage of different phases present, nodularity, nod. Count per mm^2 and nodularity percentage etc.

Here are some instances of the SG Iron tempered at 200^0c for 1 hour given below:

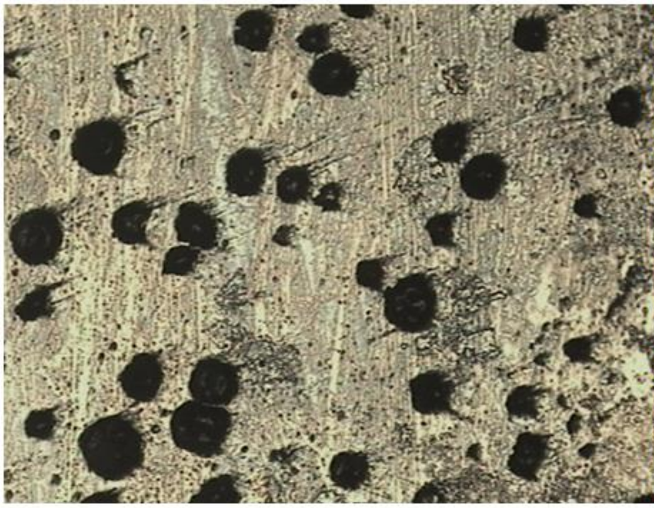


Fig 5.4.1: Original microstructure as seen under Optical microscope. (Magnification 100X)

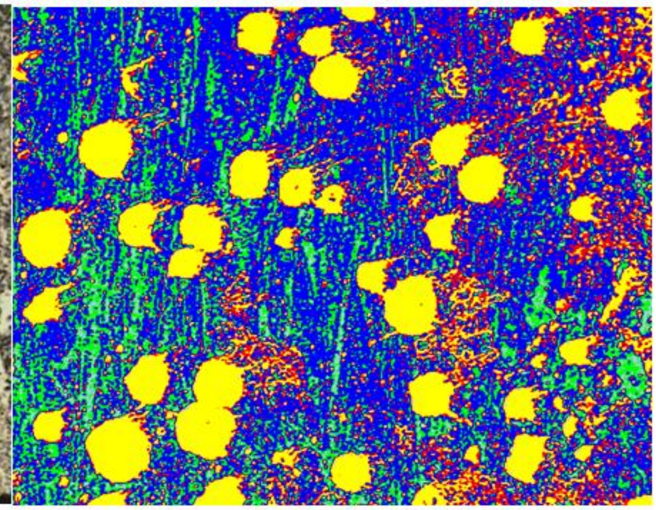


Fig 5.4.2: picture showing the presence of different phases of the original image

Here are some instances of the SG Iron tempered at 200^0c for 1.5 hours given below:

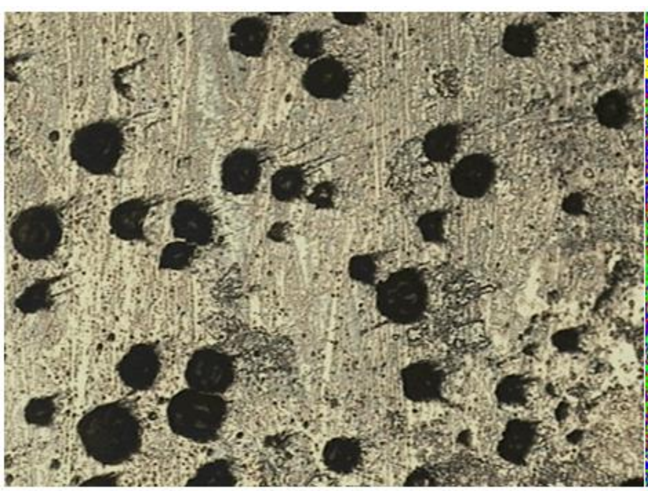


Fig 5.4.6: Microstructure of SG Iron tempered at 200^0c for 1.5 hours

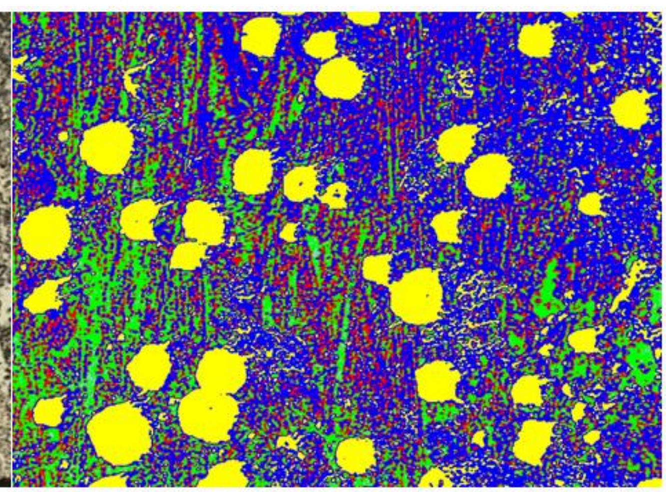


Fig 5.4.6: Image showing different phases present in original microstructure

5.5 Mechanical properties Study:

5.5.1 Hardness Testing:

The method utilized for hardness testing was Vickers hardness testing (XHB20).

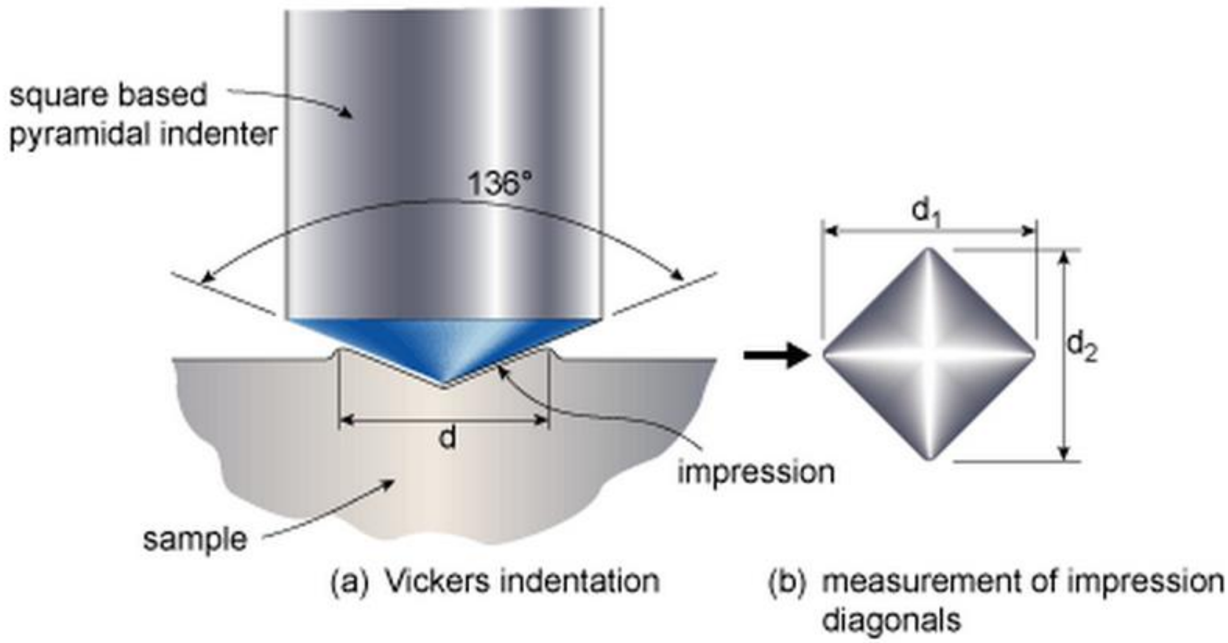


Fig 5.5.1: Vickers hardness test

In Vickers hardness test a square based pyramidal diamond indenter is used. The depth of the impression does not affect the accuracy of the reading, so the P/D^2 ratio is not important. The diamond does not deform at high loads so the results on very hard materials are more reliable. The load applied was 20 kgf for 10 seconds. Two diagonals, d1 and d2, are measured, averaged and the surface area calculated then divided into the load applied. As with the Brinell test the diagonal measurement is converted to a hardness figure by referring to a set of tables. The hardness may be reported as Vickers Hardness number (VHN).

5.5.2 Impact Testing:

Charpy V-notch test described in ASTM E23 was employed for impact testing. In this method the specimen was shaped as shown in the figure below:

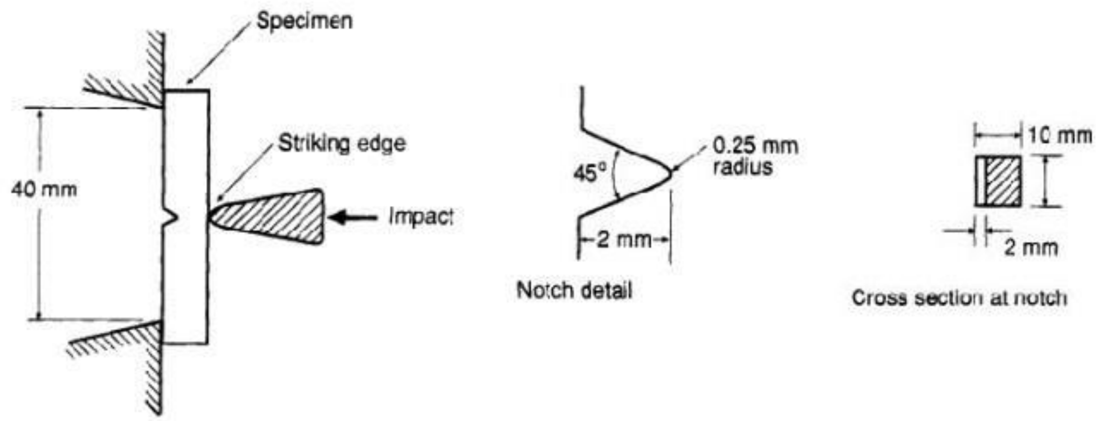


Figure 5.5.2: Charpy V-Notch Impact Testing Specimen Measurements

The process adopted is as follows:

1. The Charpy specimen was placed horizontally across supports with the notch away from the hammer.
2. The indicator pointer was slided to the left until it indicates the maximum energy range on the upper Charpy-Tension scale.
3. The pendulum arm was raised to the right until it is firmly supported by the latching mechanism.
4. The pendulum was released by pushing up on the release knob. The hammer dropped, striking the specimen, with a swing through dependent on the amount of energy absorbed by the test specimen. The indicator moved and stopped when peak swing through was registered, providing a direct reading of the energy absorbed by the specimen.
5. The indicated value from the Charpy scale was recorded.

5.5.3: Fractography

In fractographic analysis the first & foremost thing is to properly handle the specimen, so that the fracture surface does not get damaged. Thereafter the specimen is cut to appropriate size for analysis using SEM (Scanning Electron Microscope.) Then all the specimens are kept under SEM for analysis of fracture surface. A series of photographs are taken in due course of experiment which helps in determining the type of fracture that has taken place.

CHAPTER 6: RESULTS & DISCUSSIONS

MECHANICAL PROPERTIES

Specimen ID	Nodularity (%)	Pearlite content	Hardness	Impact energy (J)
200-1hr	97.601	75.271%	366.1 HV20	8.808
200-1.5hr	92.517	48.12%	345.6 HV20	10.219
200-2hr	95.630	41.245%	327.8 HV20	11.337
400-1hr	95.775	38.625%	306.5 HV20	11.432
400-1.5hr	96.364	34.586%	293.4 HV20	16.559
400-2hr	95.058	20.581%	285.8 HV20	18.653

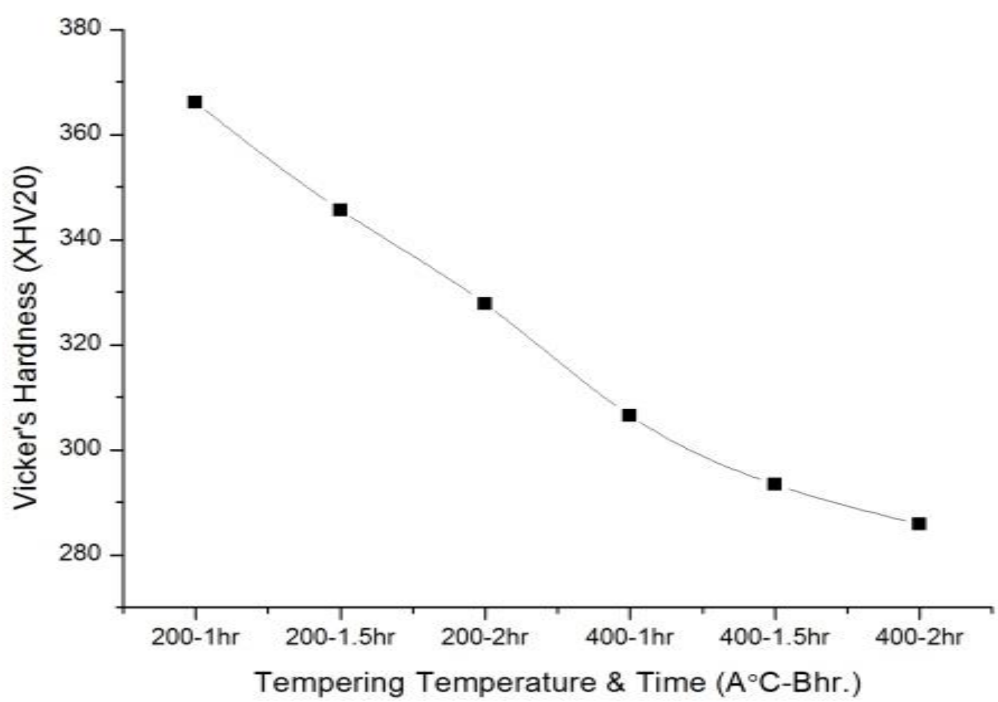


Table 6.1: Mechanical property Results and Fig 6.1: Variation of hardness w.r.t Tempering temperature & Time

The hardness values of respective specimens are represented in the figure above. It was observed that maximum and minimum hardness values obtained for specimen 200-1 hr. (366.1 HV20) & 400-2hr (285.8HV20) respectively. Also it has been observed that as the tempering time increases, hardness value decreases. Similarly it has also been observed that as the tempering temperature increases, the hardness decreases. The Izod impact energy for the specimens tempered at 200°c & 400^0c are observed to be increasing with increase in tempering time.

MICROSTRUCTURAL INVESTIGATION

The microstructure of each heat treated specimens was presented in figure below. The microstructure of each specimen was observed to have pearlitic/ferritic matrix with different volume fraction of ferrite and pearlite. However very less amount of martensite (14.269 %.) was found in specimen 200-1.5hr.

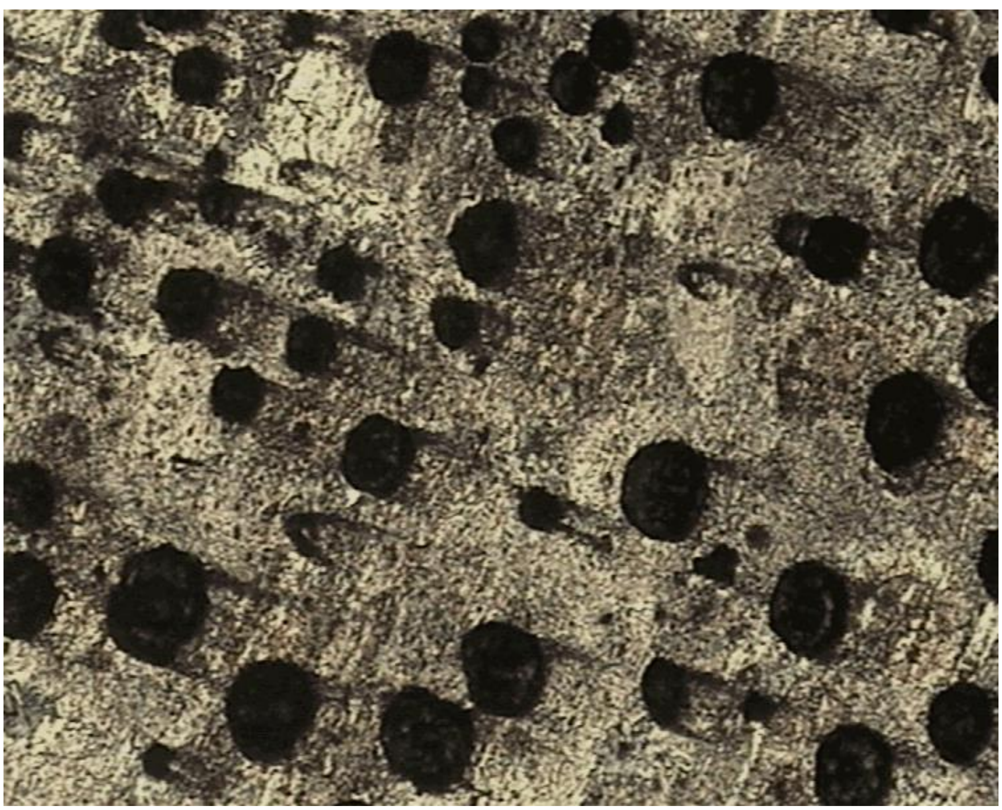
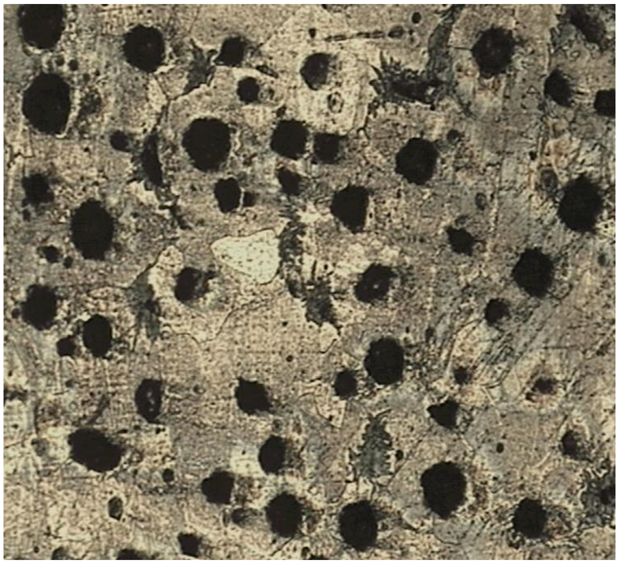


Fig. 6.2: Tempered at 200^0c-1hr



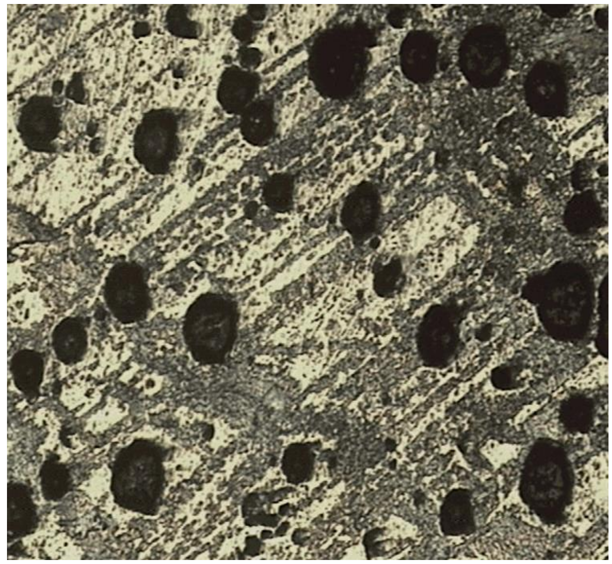


Fig. 6.3: Tempered at 200^0c-1.5hr

Fig.6.4: Tempered at 200^0c-2hr

Fig. 6.5: Tempered at 400^0c-1hr

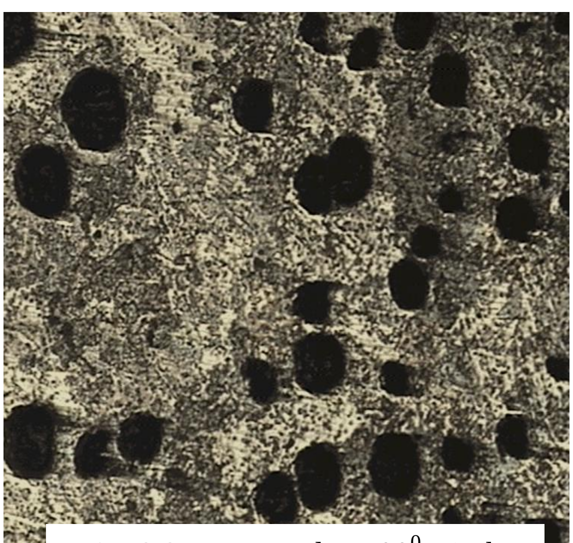


Fig. 6.6: Tempered at 400^0c-1.5hr

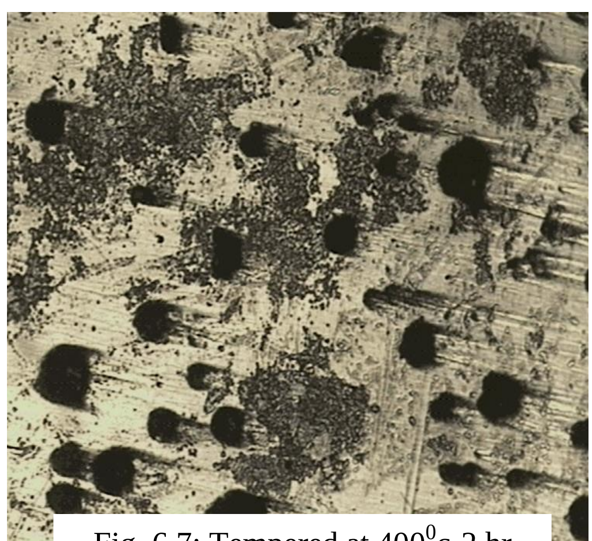


Fig. 6.7: Tempered at 400^0c-2 hr

FRACTOGRAPHIC INVESTIGATION

The fracture surfaces of each specimen after Izod impact test was observed under FESEM at 250X and 1000X, shown in the figure below. Each specimen showed a mixed mode of fracture i.e., partially ductile and partially brittle in nature. At lower magnification characteristics of brittle fracture i.e., flat surfaces with river markings throughout the matrix is clearly visible with a very less area indicating towards ductile fracture characteristics i.e., presence of dimples. These areas when viewed at higher magnification it was confirmed that dimples were present at some areas in the matrix which is a characteristic of ductile fracture.

From the following pictures of the fracture surface it is clearly visible that the fracture consists of mixed mode i.e. both the ductile fracture and brittle fracture is prevalent in the surface. The evident that support the presence of ductile fracture are the dimples and the sheared void like structure represented by white color in the figure. And the evident that support the presence of brittle fracture are the flat surfaces which are represented by gray color in the fracture surface. Thus it is a mixed mode of fracture having both brittle & ductile fracture surfaces.

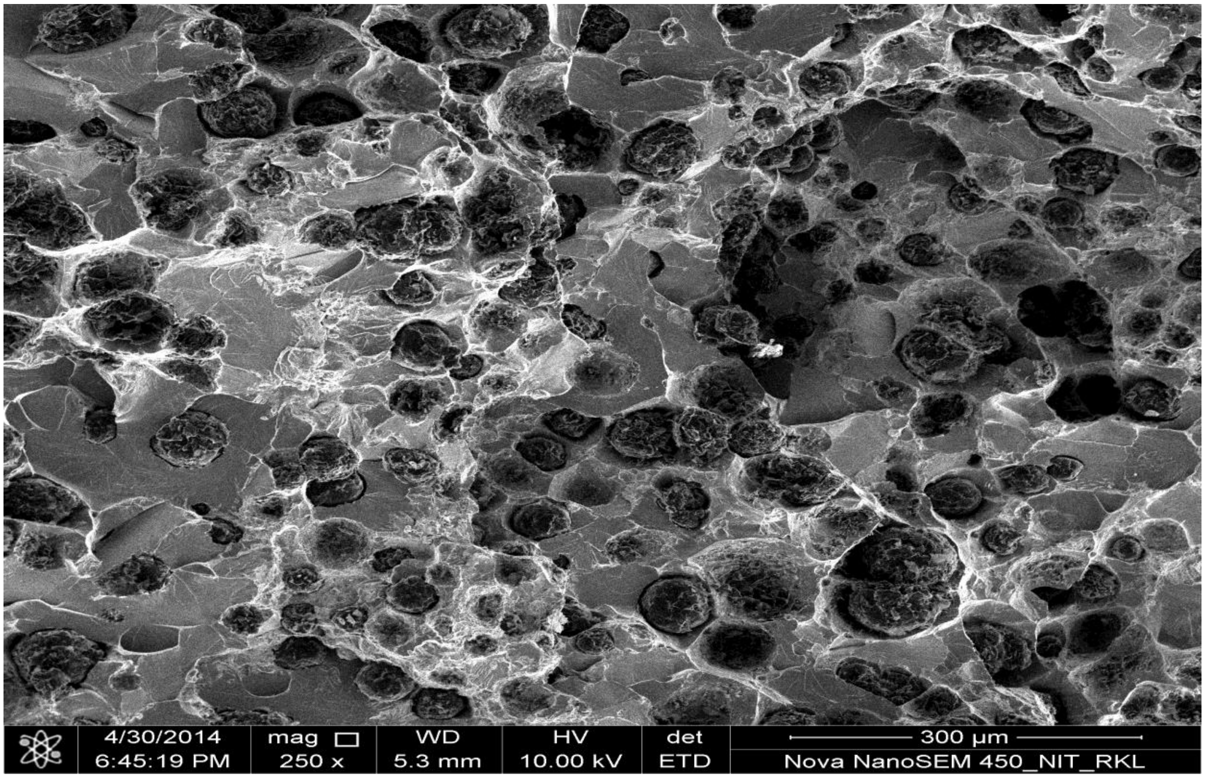


Fig. 6.8: Fracture surface of Specimen Tempered at 200^0c-1hr: 250X

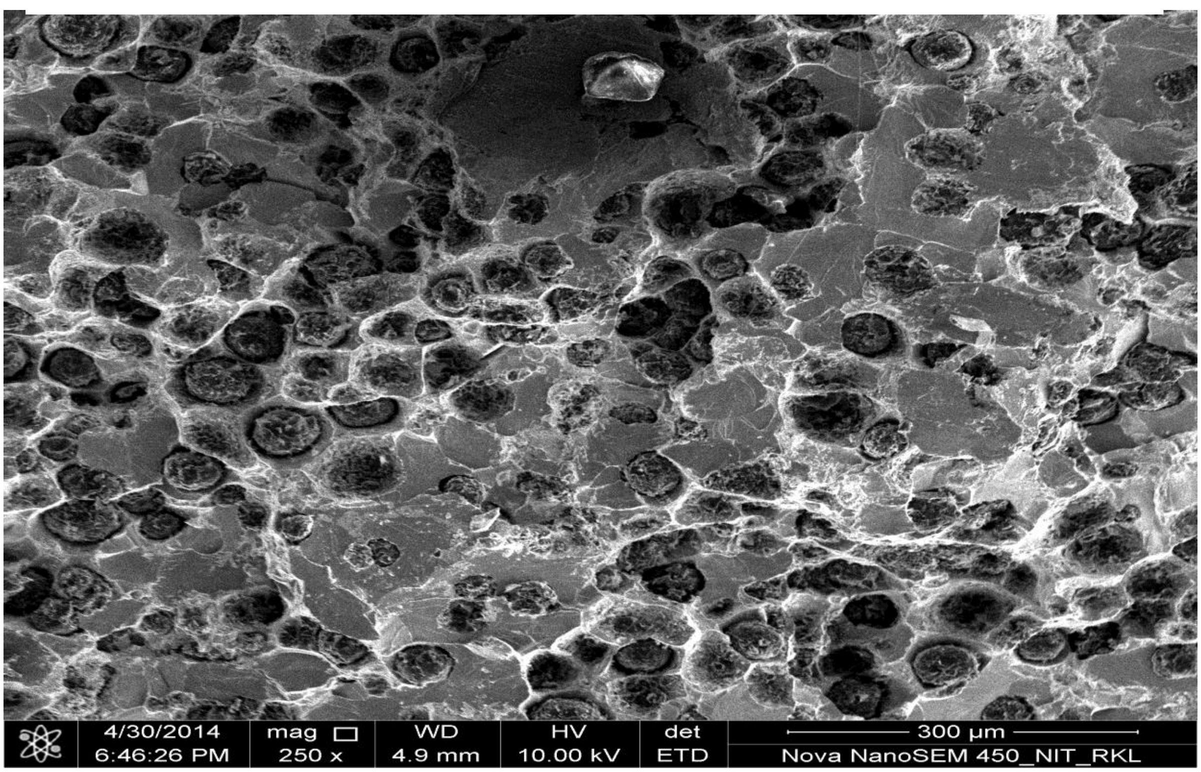


Fig. 6.9: Fracture surface of Specimen Tempered at 200^0c-1.5hr: 250X

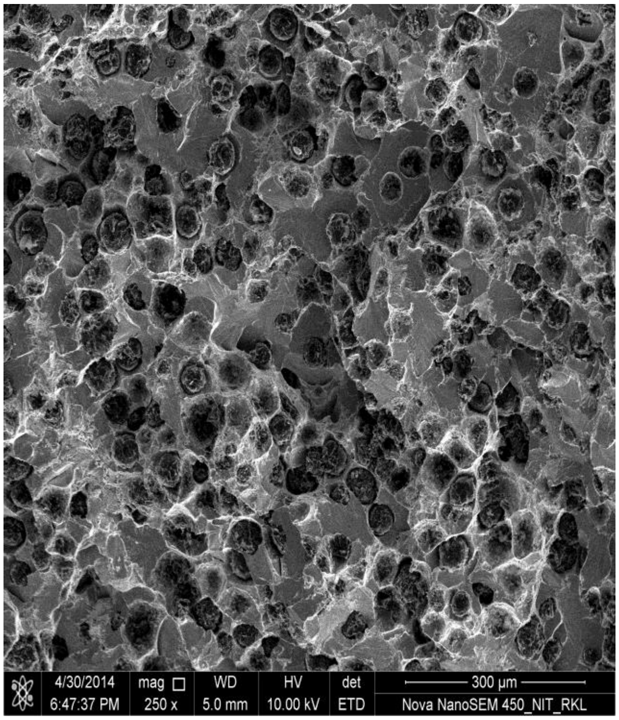


Fig. 6.10: Specimen Tempered at 200^0c-2hr: 250X

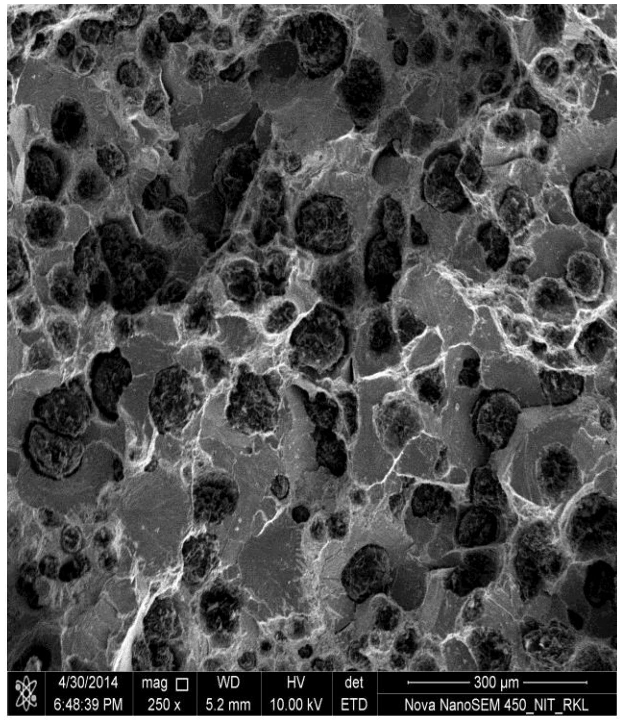


Fig. 6.11: Specimen Tempered at 400^0c-1hr: 250X

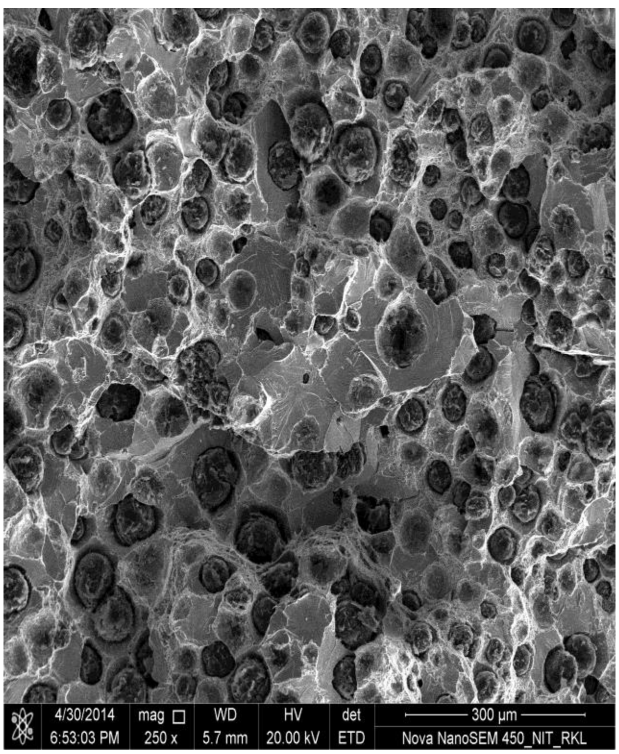


Fig. 6.12: Specimen Tempered at 400^0c-1.5hr: 250X

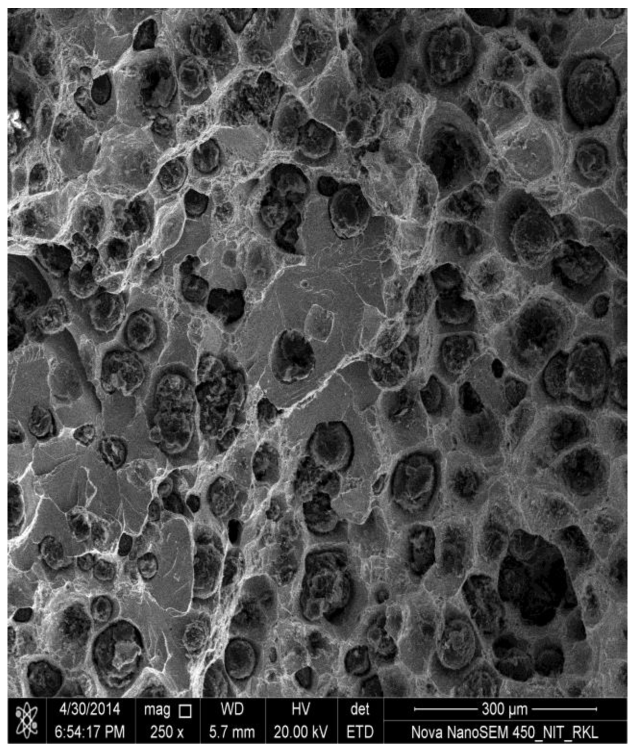


Fig. 6.13: Specimen Tempered at 400^0c-2 hrs. 250X

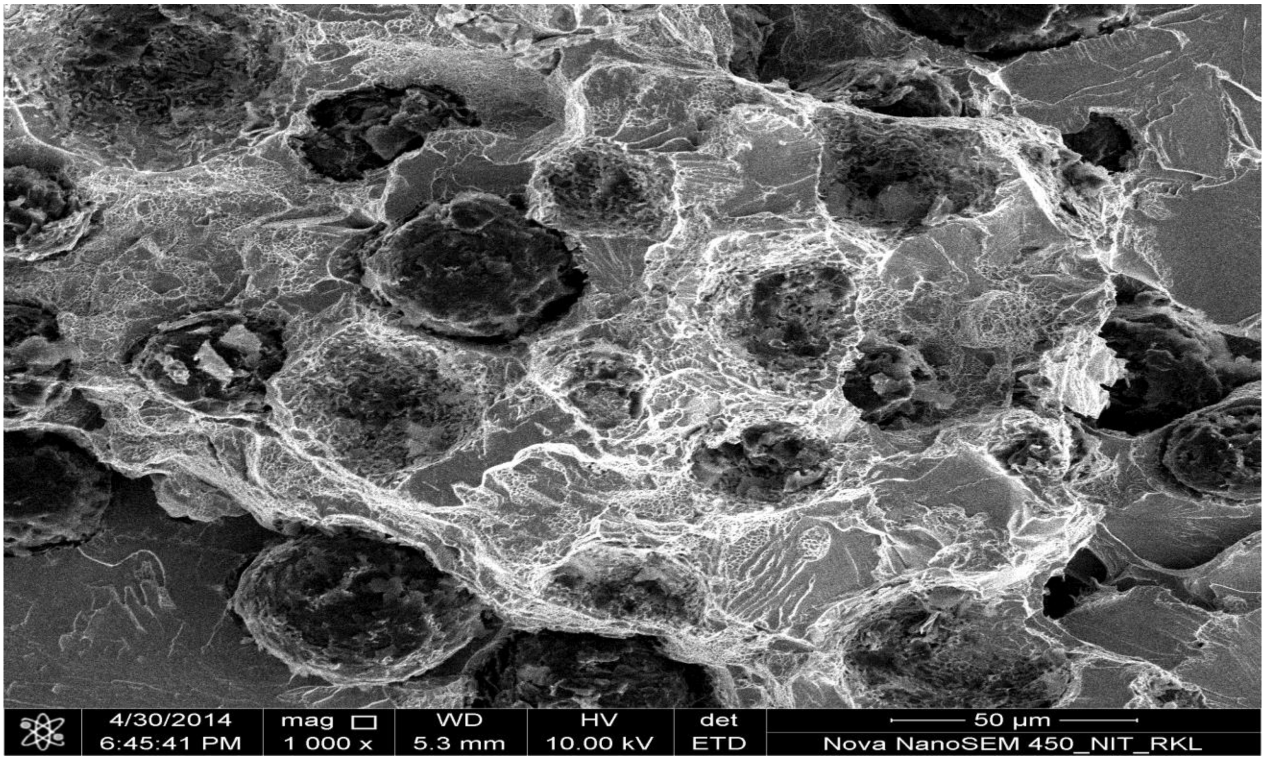


Fig. 6.14: Specimen Tempered at 200^0c-1hr: 1000X

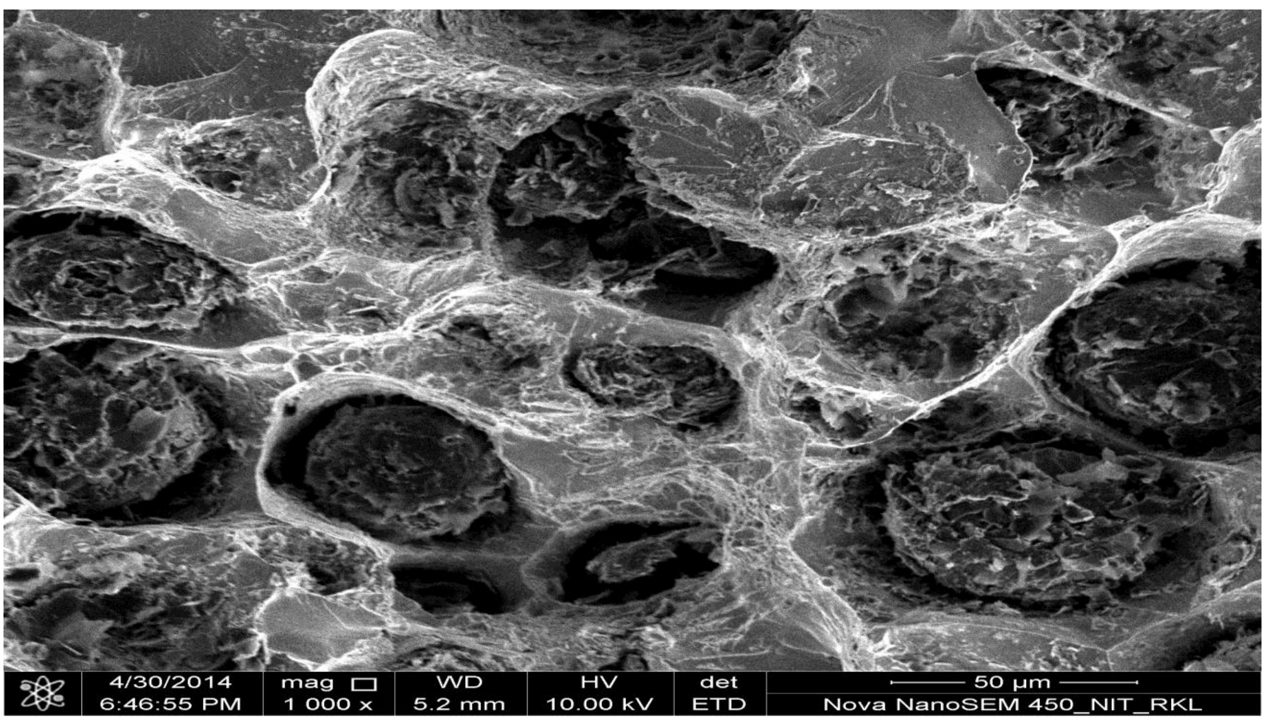


Fig. 6.15: Specimen Tempered at 200^0c-1.5hr: 1000X

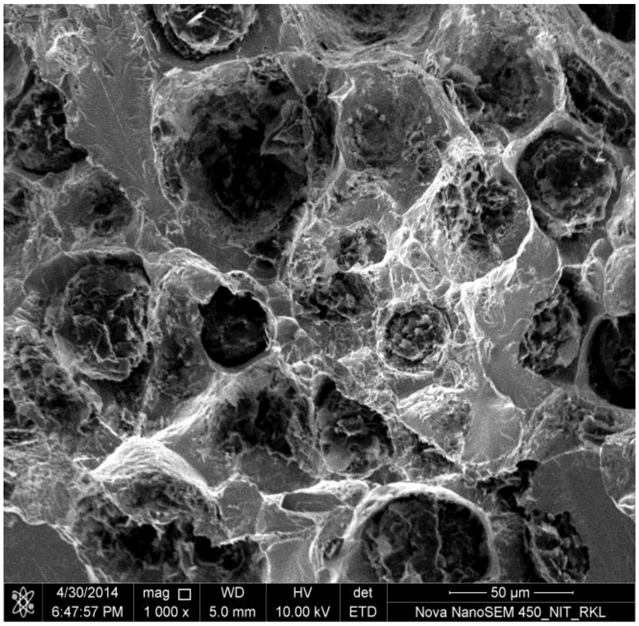


Fig. 6.16: Specimen Tempered at 200^0c-2 hr. 1000X

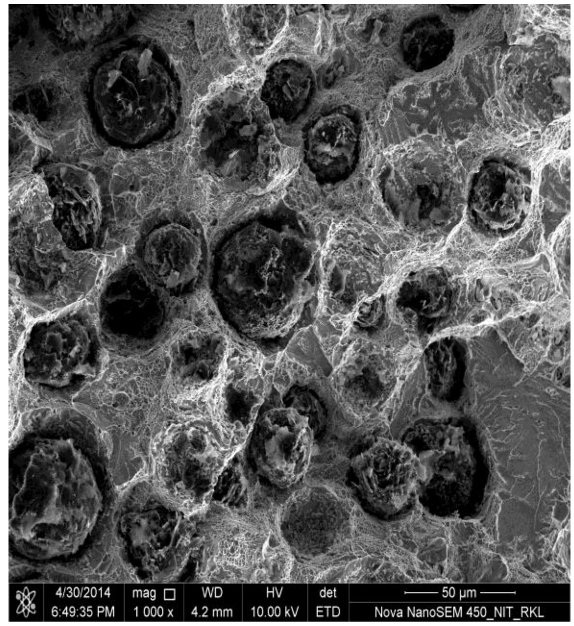


Fig 6.17: Specimen Tempered at 400^0c-1 hr. 1000X

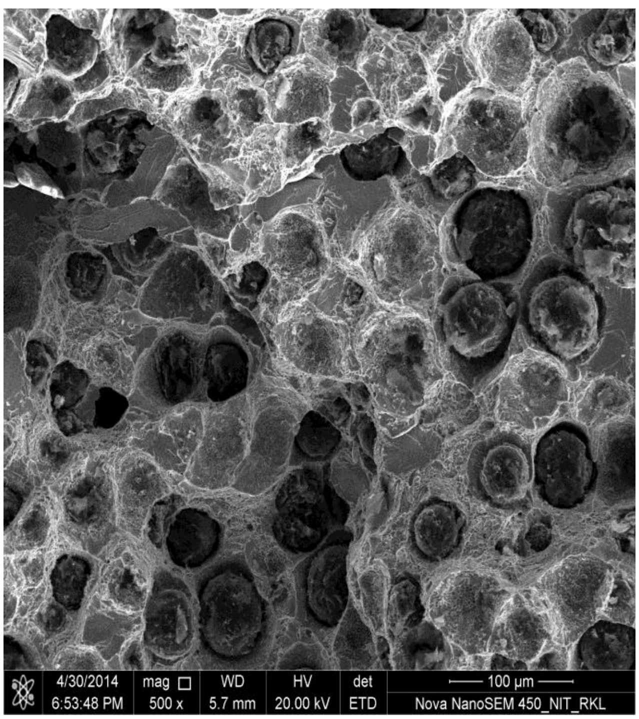


Fig. 6.18: Specimen Tempered at 400^0c-1.5 hr. 1000X

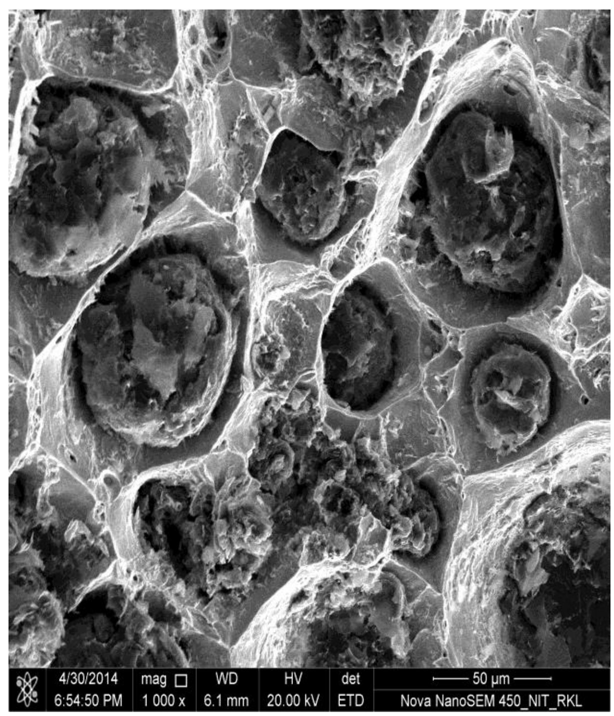


Fig. 6.19: Specimen Tempered at 400^0c-2 hr. 1000X

X-RAY DIFFRACTION ANALYSIS

The XRD patterns for specimens treated at 200°C & 400°C are presented in the figure below. The patterns were analyzed with the help of Philips X-pert Highscore and JCPDS softwares. It was found that each specimen is having BCC crystal structure confirmed by (110), (200), (211) planes obtained for peaks at 44.64°, 64.80°, 82.52° respectively.

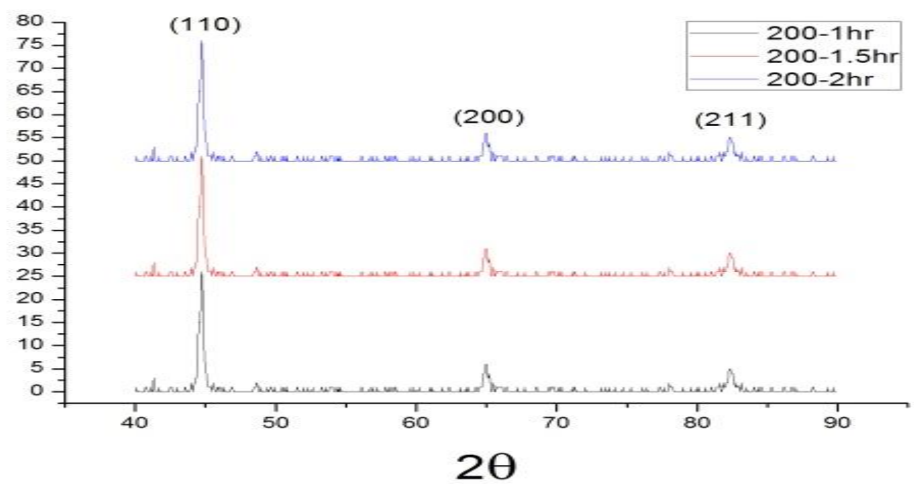


Fig. 6.20 : XRD pattern for specimen tempered at 200^{0}c

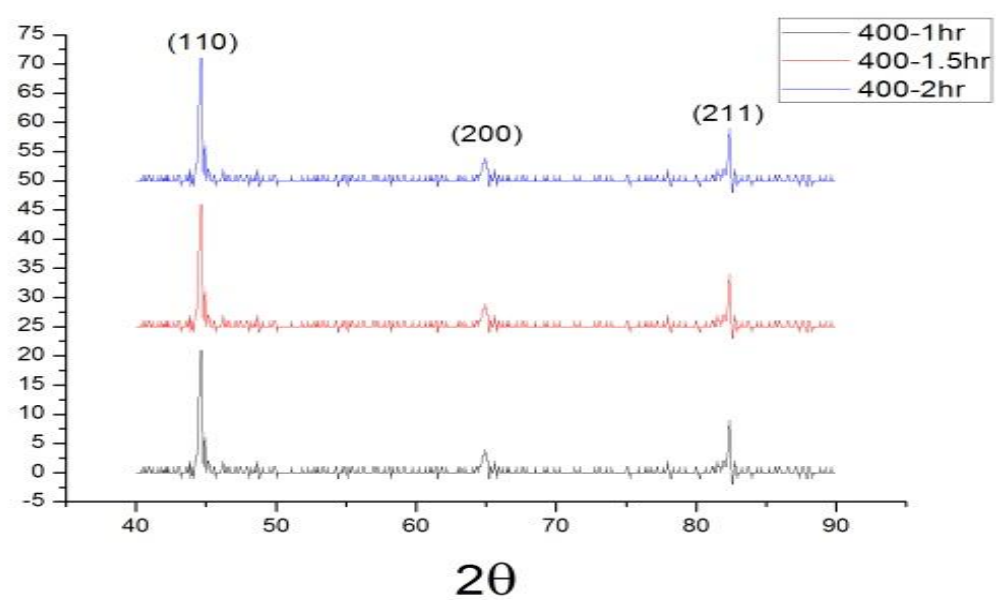


Fig. 6.21 : XRD pattern for specimen tempered at 400^{0}c

CHAPTER 7: CONCLUSION

From the above results it can be concluded that the properties of Spheroidal graphite Iron can be enhanced or altered according to service condition and application requirements by just altering the temperature & time of tempering. Earlier limitations on the usage of Spheroidal graphite iron due to the limited knowledge of property enhancement processes can now be overcome by various heat treatment techniques. It has been found that by heat-treatment operations like austenising & tempering their brittle behavior can be transformed to ductile behavior applicable in various applications.

The following information can be extracted from the above experiment viz.:

- As the tempering temperature & time increases the hardness of the spheroidal graphite iron decreases.
- As the tempering temperature & time increases the Izod impact energy increases, this means the energy absorption capacity of Spheroidal graphite iron increases as the time & temperature of tempering increases.
- Hardening & tempering leads to mixed mode of fracture i.e. partially ductile & partially brittle after impact test.
- From the XRD analysis it has been confirmed that each specimen is having a bcc crystal structure.

Hence it can be concluded that Spheroidal graphite iron does have multifaceted applications because of its wide range of properties which can be easily extracted by controlled heat treatment process like hardening & tempering at different temperatures & for different time period.

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